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Characterization of CO_2 emissions during construction of reservoir embankment elevation in South Korea

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Abstract

Purpose The environmentally friendly construction of agricultural infrastructure is much needed for sustainable development because construction is recognized as a cause of environmental degradation. The objective of this study was to estimate and characterize carbon dioxide (CO_2) emissions during construction of agricultural reservoir embankments for the quantitative environmental assessment and management of CO_2 emissions using life cycle assessment method.

Methods Two reservoirs with different foundation treatment and construction components were selected in this study and their characteristics in CO_2 emissions were compared. And CO_2 emissions were calculated separately for each of the following major components: construction materials, equipment, and transport. The basic unit of CO_2 emissions for construction materials was calculated using the 2009 input–output tables in Korea and the basic unit of CO_2 emissions for equipment of transport and construction was also calculated based on the amount of fuel used in a unit time.

Results and discussion According to the study results, the construction of a water supply process appeared to generate the most emissions among all processes for the two sites. Emissions due to equipment were the highest in site A, while materials generated the most emissions in site B. Differences in emissions are due to differences in the construction process. While the operation time of the equipment in site A increased due to the cofferdam process and a large amount of cement was used in the foundation process in site B.

Conclusions Characteristic of CO_2 emissions differs with different construction processes and thus construction processes need to be optimized for environmental friendly development of agricultural infrastructure through estimation and characterization of CO_2 emissions.

Keywords Agricultural infrastructure · CO_2 emissions · Construction · Input–output tables · Reservoir embankment elevation

1 Introduction

Climate changes that are currently causing many problems have gained increasing attention over the past decades. Many efforts have been undertaken to reduce damages by climate changes in many countries (Ortiz et al. 2009). In Korea, a huge agricultural civil engineering project named Four Major Rivers Restoration Project is currently underway to establish countermeasures against floods and drought, which occur frequently, and to meet the increasing demand for water-related leisure activities with income growth (Kim 2010). The importance of agricultural reservoirs is increasing because the global water demand for food production for the growing world population is expected to rise, and may occur under dooming water scarcity (Wisser et al. 2010). Therefore, the elevation of reservoir embankments is planned and currently underway to prevent damages from floods and the deterioration of agricultural reservoir embankments while securing agricultural water resources (Lee et al. 2011). This project includes a total of 113 locations, 96 of which are located in the basins of the major 4 rivers and 17 in other river basins.

However, activities associated with the construction of agricultural infrastructures are not recognized as environmentally

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friendly development although agricultural infra-structures are important parts of human society. This is because various natural resources are consumed, including energy resources, water, land, and minerals, such that many types of pollutants are released back into the global/regional environment on a large scale (Erlandsson and Borg 2003; Li 2006; Fairbairn et al. 2010). Environmental improvement will be crucial for sustainable development, and an environmental assessment is required in the agricultural infrastructure construction sector.

In the past, the environmental impact of construction projects was only assessed in a qualitative manner. Thus the quantitative assessment and management should be introduced for accurate analysis in construction sector (Richard et al. 2007). Recently, CO_2 emissions have been evaluated quantitatively in many industry sectors (Bilec et al. 2006). CO_2 is a major cause of global warming and accounts for 80 % of total greenhouse gas emissions (Gustavsson et al. 2010). International regulations regarding the reduction of CO_2 emissions were adopted through the Kyoto Protocol on Global Warming in 1997 to prevent global warming (Barrett 1998; Springer 2003; Li 2006). Korea did not participate but will soon have to reduce greenhouse gas emissions across all industries because the obligation is likely to be extended to developing countries in the future (Kwun and Kim 2007). The construction industry in particular, which constitutes about 40 % of the total energy demand, approximately 48 % of total material use, and roughly 42 % of total CO_2 emissions, has been identified as one of the main sectors contributing to greenhouse gas emissions in Korea (Seo and Hwang. 1998; Kim et al. 2004). However, an analysis of CO_2 emissions in the construction industry is less developed today than in other industries, but appears to be developing quickly (Eaton and Amato 1998). Accordingly, an evaluation of the environmental effect of agriculture construction is required for the management of CO_2 emissions during the construction process.

Such an evaluation requires many studies on the assessment of life cycle CO_2 emissions ($LCCO_2$) from buildings and other structures. Suzuki and Oka (1998) estimated life cycle energy consumption and CO_2 emissions of office buildings in Japan, and Wu et al. (2012) analyzed life cycle energy consumption and CO_2 emissions of an office building in China. Much previous $LCCO_2$ research on construction industry focused on energy consumption of buildings (Erlandsson and Borg 2003; Gustavsson et al. 2010; Ramesh et al. 2010; Rosselló-Batle et al. 2010; Tae et al. 2011a, b; Verbeeck and Hens 2010a; 2010b) and construction materials (Borjesson and Gustavsson 2000; Flower and Sanjayan 2007; Tae et al. 2011a, b; Hong et al. 2012). Some researchers recognized construction as a major source of CO_2 emissions since substantial amounts of CO_2 are generated during infrastructures construction such as the road (Park et al. 2003). Treloar et al. (2004) proposed a hybrid LCA method that uses input–output data to fill in those gaps routinely left in conventional LCA inventories for road construction and use. Bilec et al. (2006) reviewed existing hybrid models, along with a recommendation of a hybrid model for construction. Sharrard et al. (2008) applied a hybrid LCA model to analyze efficiency, economic effect, and environmental impact of construction activities, but did not consider construction materials or operational impacts. However, little effort in researching construction processes of agricultural infrastructure has been undertaken; thus, more studies that consider the large scale of agricultural infrastructure and its impact on the environment are required. The objective of this study was to characterize CO_2 emissions through estimating CO_2 emissions for each process during the construction of a reservoir embankment elevation and to propose a schem for

Fig. 1 The framework of input–output tables (Leontief 1936)

			Purchasing sectors														
			Intermediate demand						Final demand							Import	Total
			1	⋯	j	⋯	n	W	Consume	⋯	Invest	⋯	Export	Y		(deduct)	Production
Producing sectors	Produced input	1	X_{11}	⋯	X_{1j}	⋯	X_{1n}	W_1	C_1	⋯	I_1	⋯	E_1	Y_1		M_1	X_1
		:	:		:		:	:	:		:		:	:		:	:
		i	X_{i1}	⋯	X_{ij}	⋯	X_{in}	W_i	C_i	⋯	I_i	⋯	E_i	Y_i		M_i	X_i
		:	:		:		:	:	:		:		:	:		:	:
		n	X_{n1}	⋯	X_{nj}	⋯	X_{nn}	W_j	C_n	⋯	I_n	⋯	E_n	Y_j		M_j	X_j
		U	U_1	⋯	U_j	⋯	U_n										
	Value input	Compensating of employees	R_1	⋯	R_j	⋯	R_n										
		Operating surplus	S_1	⋯	S_j	⋯	S_n										
		Consumption of fixed capital	D_1	⋯	D_j	⋯	D_n										
		Net production tax	T_1	⋯	T_j	⋯	T_n										
		V	V_1	⋯	V_j	⋯	V_n										
	Total consumption		X_1	⋯	X_j	⋯	X_n										

Table 1 Basic information and reinforcement status regarding study areas

Site Location		A Chungheongbuk-do, Korea	B Gyeongsangnam-do, Korea
Developments	Basin area	2,271 ha	1,160 ha
	Irrigation area	859.3 ha	314.0 ha
	Additional water capacity	1,018,000 m^3	1,011,000 m^3
Major works	Height	35.5 m→36.75 m (increase 1.25 m)	47.5 m→50.7 m (increase 3.2 m)
	Length	283 m→418 m (increase 135 m)	302 m→356 m (increase 54 m)
	Water-intake facilities	Intake tower reinforcement	Intake tower reinforcement
	Relocating road	New establishment 2 set, 575 m	New establishment 1 set, 100 m
	Pumping station	New establishment of second stage pumping station	–
Construction cost basis price of 2009		KRW 18.7 billion	KRW 24.6 billion

the management of CO_2 emissions in the agricultural infrastructure construction industry.

2 Theory

The primary LCA methods are LCA and economic input–output (EIO) LCA (Lave et al. 1995; Hendrickson et al. 1998). The process method systematically computes the known environmental inputs and outputs by utilizing a process flow diagram. The scope of the process model continues to the point where the flow between process and emissions are negligible. The process approach was further developed with the framework established in the ISO 14040 series (ISO 2003; 2006a; 2006b). This approach requires data collection from public sources, company or product specific information, and published research. Process model can analyze specific processes and identify process improvements (Bilec et al. 2006). However, although data availability and modeling have improved, the effectiveness of the process LCA can still be limited when used to assess service industries due to the complexity of the evaluated services and the difficulty of attributing impacts to the monetary flows that propel service industry revenue (Shrake et al. 2013).

Another LCA method is economic input–output (EIO) analysis, which was developed by Wassily Leontief in 1936. Input–output analysis is an important quantitative economic technique that determines the interdependency between the various branches of a national economy and even between the various branches of different, possibly competing, economies. Input–output analysis are used to make economic policy decisions and measure policy effects because they help to analyze the ripple effect caused by final demand by separating all industries (Thijs 2009). Central to the concept of input–output analysis are the ideas of total output (X), intermediate demand (W), and final demand (Y). These concepts are outlined in Fig. 1. EIO-LCA combines environmental data with an economic input–output (I-O) model to determine primary energy, economic, and environmental releases associated with producing a product. EIO-LCA has also been used to assess the impacts of services, as it is better suited to deal with the impacts of financial flows to capture the scope 3 emissions (Rosenblum et al. 2000; Suh et al. 2003; Shrake et al. 2013). This approach has the advantage of estimating a basic unit for all industries easily using only the input–output tables, but it is limited by the fact that the basic unit for all goods is calculated based on the national average. Data of those are aggregated level and identification of process improvements is difficult. Product use and end-of-life options are not included, either (Bilec et al. 2006).

Hybrid LCA offers the ability to combine the strengths of both process and I-O-based LCA approaches in order to avoid some of the issues associated with both methods (Bilec et al. 2006; Suh 2006). Hybrid LCA allows for flexibility within the inventory of assessment, which aids in setting appropriate boundaries and data collection. Hybrid LCA is

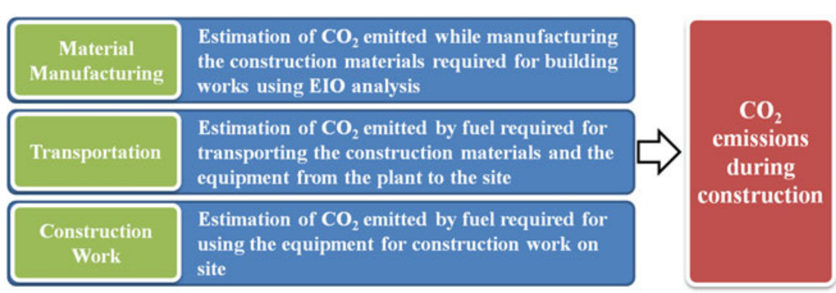

Fig. 2 The boundary and flow of process for the estimation of CO_2 emissions

Table 2 Information regarding energy resources (IPCC 2007)

Classification		Unit	Caloric value (kcal/unit)	Coefficient of CO_2 emissions (kg CO_2/kcal)	Combustion rate
Oil	Gasoline	L	8,000	0.000287	0.990
	Jet	L	8,750	0.000296	0.990
	Lamp oil	L	8,800	0.000298	0.990
	Diesel	L	9,050	0.000307	0.990
	Heavy oil	L	9,600	0.000321	0.990
Gas	LPG	kg	12,000	0.000261	0.990
	LNG	kg	13,000	0.000231	0.995
	City gas	m^3	10,550	0.000234	0.995
Coal	Anthracite	kg	4,650	0.000403	0.980
	Bituminous	kg	6,200	0.000388	0.980
Electricity		kW/h	860	0.000289	–

often used to assess production of products such as laptops, incorporating economic data where process manufacturing or material data is unavailable or proprietary (Deng et al. 2011; Shrake et al. 2013).

Because the construction industry is so complex and consume many types of materials, modeling construction processes to better understand their environmental implications could be best achieved with the process LCA approach (Harris 1999; Park et al. 2003; Sharrard 2007). However, process LCAs are data intensive and time-consuming given the unique nature of construction projects. Current process LCA models either ignore, underestimate, or inadequately address the environmental effects of the construction process (Sharrard et al. 2008). The scale of construction works associated with agricultural infrastructures is also enormous; therefore, research on the application of hybrid analysis in the agricultural industry is required to address the effects of agricultural infrastructures on the environment.

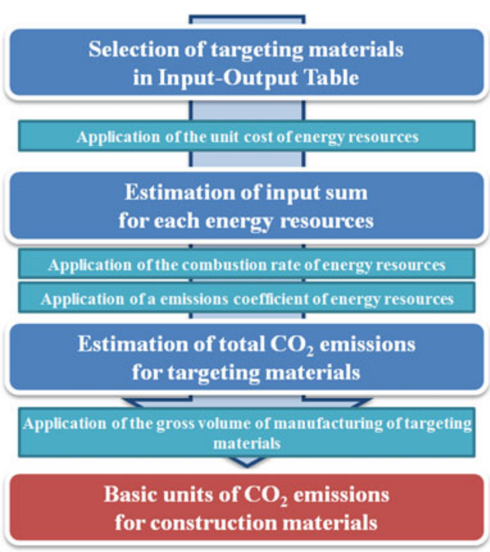

Fig. 3 EIO analysis procedure for the estimation of CO_2 emissions from construction materials

3 Materials and methods

3.1 Study area

The reservoirs, where the major method of reservoir embankment elevation was constructed and the accurate construction statement was prepared, were selected to characterize CO_2 emissions during reservoir embankment elevation. And to compare the characteristics of the CO_2 emissions caused by the difference in the detailed process, two reservoirs were selected. The status of each reservoir is presented in Table 1.

3.2 Methods

CO_2 is emitted during various processes in the life cycle of large-scale agricultural infrastructure construction. In this study, the life cycle is limited from material manufacturing to the construction work, over the entire life cycle of the embankment because the embankment is installed abidingly without demolition. CO_2 emissions for each of the individual processes were estimated separately based on construction materials, equipment, and transport. Figure 2 describes the boundary and flow of process for the estimation of CO_2 emissions.

Datasets for CO_2 emissions for each construction material were obtained from the EIO analysis because the calculation of a basic unit of CO_2 emissions for construction materials using the process method is difficult due to the large range and variety of construction materials used. The basic unit of CO_2 emissions for construction materials was calculated using the 2009 input–output tables, which contains data for 403 industrial

Table 3 Basic units of CO_2 emissions for major construction materials and equipment

Part	Classification	Standard	Basic unit of CO_2 emissions	Unit
Material	Ready-Mixed Concrete	–	4.668×10^{-4}	kg CO_2/KRW
	Rebar	–	5.592×10^{-5}	
	Ascon	–	2.031×10^{-4}	
	Cement	–	1.737×10^{-2}	
	Exercise equipment	–	7.620×10^{-5}	
Equipment	Dump truck	15 ton	60.35	kg CO_2/h
	Back hoe	0.7 m^3	38.93	
		1.0 m^3	65.44	
	Bulldozer	19 ton	79.77	
	Roller	Vibration 10 ton	51.49	
	Crain	Truck 20 ton	28.39	
		Truck 25 ton	31.39	
	Waterjet pump	96 kW	81.14	
	Vibration pile hammer	45 kW	11.18	
		60 kW	14.61	

sectors in Korea (The Bank of Korea 2011). Oil (gasoline, jet fuel, lamp oil, diesel, and heavy oil), gas (LPG, LNG, and city gas), coal (anthracite and bituminous), and electricity were selected as energy resources for the EIO analysis. The information of energy resources, which was provided by the IPCC in 2006, was used. The coefficient of CO_2 emissions from fuels used to calculate CO_2 emissions is given in Table 2. How to calculate CO_2 emissions of construction materials, using the EIO analysis, is illustrated in Fig. 3.

The basic unit of CO_2 emissions for equipment of construction and transport was also calculated based on the amount of fuel (gasoline, diesel, etc.) used in a unit time. The standard estimating for construction works in 2009 (Korean institute of construction 2009) was used for calculating working times and the amount of fuel used for the equipment in a unit time. Information regarding energy resources, which was provided by the IPCC (2006), was also used from calculate CO_2 emissions of construction equipment operation.

4 Results and discussion

4.1 Estimation of the basic unit of CO_2 emissions

The basic unit of CO_2 emissions from construction materials and equipment was estimated using the input–output tables (The bank of Korea 2011) and the standard estimating for construction works (Korean institute of construction 2009) as described above, respectively. The basic unit for construction materials was calculated as a unit of currency (KRW,), and that for construction equipment was estimated by the amount of fuel used per a unit time. The major transport equipment was defined as a 15-ton dump truck, which is most commonly

Table 4 Estimated CO_2 emissions for each site

Site	Division	CO_2 emissions (kg CO_2)		
		Water supply	Appurtenant	Total
A	Material	3.886×10^{5}	2.877×10^{5}	6.763×10^{5}
	Transport	4.641×10^{5}	3.288×10^{4}	4.970×10^{5}
	Equipment	1.899×10^{6}	1.277×10^{5}	2.026×10^{6}
	Total	2.751×10^{6}	4.483×10^{5}	3.200×10^{6}
B	Material	2.165×10^{6}	6.903×10^{4}	2.234×10^{6}
	Transport	1.149×10^{5}	1.472×10^{3}	2.009×10^{5}
	Equipment	1.061×10^{6}	1.321×10^{4}	1.075×10^{6}
	Total	3.341×10^{6}	7.214×10^{4}	3.509×10^{6}

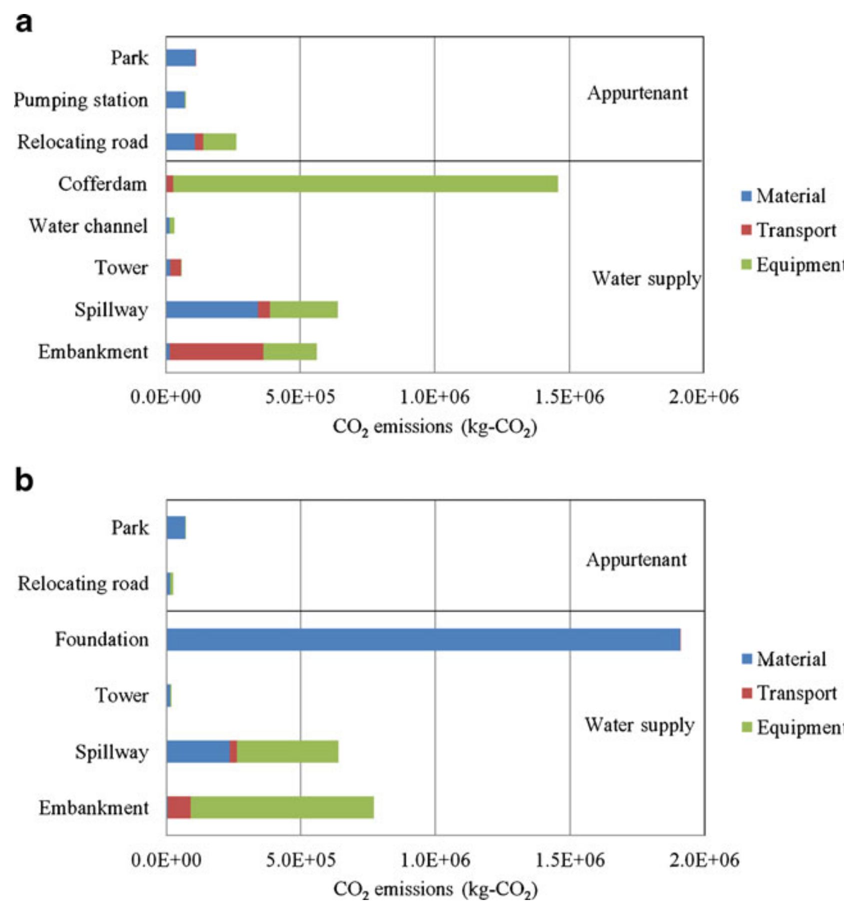

Fig. 4 Characteristics of CO_2 emissions for specific processes in site A (**a**) and site B (**b**)

used. The results obtained when using the aforementioned basic unit of CO_2 emissions from major construction materials and equipment are summarized in Table 3.

Cement had the largest basic unit of CO_2 emissions among the major construction materials and is one hundred times as great as that of rebar, whose normalized CO_2 emissions is the lowest. Emissions from ready-mixed concrete, asphalt concrete, and exercise equipment were higher than those of the other major construction materials. The 96-kW waterjet pump and the 19-ton bulldozer showed high emissions, while electric vibrating pile hammer generated relatively low emissions among all construction equipment.

Table 5 Estimated CO_2 emissions from materials

Division	CO_2 emissions (kg CO_2)	
	Site A	Site B
Ready mixed concrete	2.430×10^5	2.135×10^5
Rebar	4.125×10^4	4.103×10^4
Ascon	2.714×10^4	4.553×10^3
Cement	5.000×10^3	1.916×10^6
Steel pipe	1.189×10^4	2.324×10^3
Rubber wire	1.561×10^5	–
Water pump	4.388×10^4	–
Etc.	1.481×10^5	6.982×10^4

4.2 Characteristics of CO_2 estimation for individual process

CO_2 emissions may vary substantially when different construction techniques and materials are incorporated into a construction process. Therefore, the entire process of reservoir embankment elevation was divided into water supply and appurtenance. The CO_2 emissions from each individual process were estimated separately based on construction materials, construction equipment, and transport. The CO_2 emissions from each individual process were calculated using a basic unit of CO_2 emissions estimated, previously, based on a breakdown of the construction cost estimated for each site (Korea Rural Community Corporation 2010). The estimated CO_2 emissions from each process and part are shown in Table 4.

The total emissions from site B are slightly higher than that from site A. The water supply process showed the highest CO_2 emissions in both sites because water supply is the greatest component of total construction cost. The emissions of specific parts vary between the two sites. Emissions from construction equipment constitute the largest

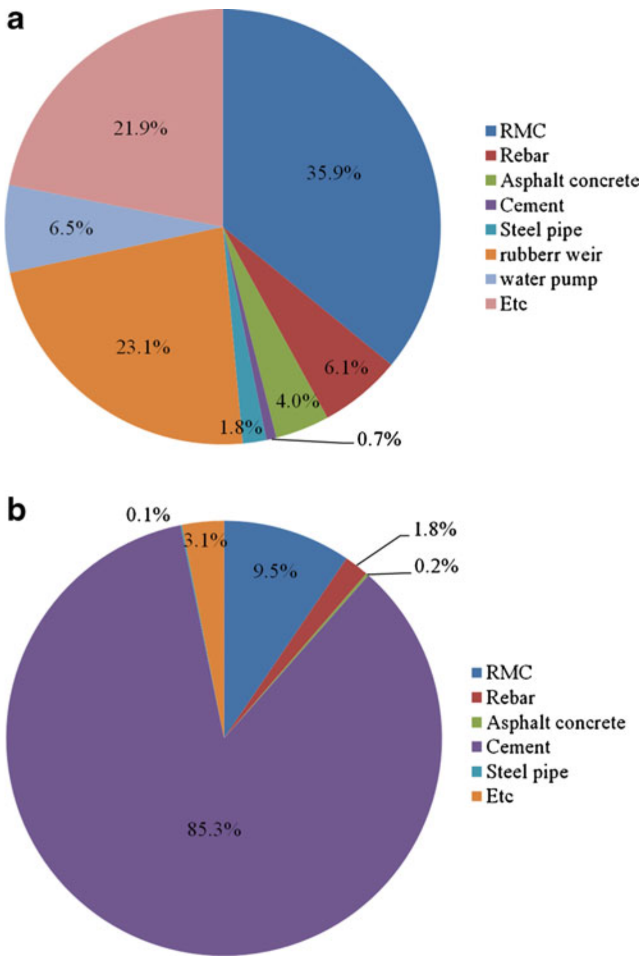

Fig. 5 Characteristics of CO_2 emissions for materials part in site A (**a**) and site B (**b**)

fraction of all emissions, 63.3 %, in site A, whereas emissions from construction materials constitute the largest fraction of all emissions, 63.7 %, in site B.

The entire reservoir embankment expansion process was broken down into sub-processes according to the characteristics of each site for an accurate assessment of emissions. The water supply process was classified into embankment, spillway, intake tower, water channel, cofferdam, and the appurtenant process was divided into relocating road, pumping station, park in site A. In site B, the water supply process was classified into embankment, spillway, intake tower, and the appurtenant process was divided into relocating road and park.

Table 6 Estimated CO_2 emissions for the transport part

Division	CO_2 emissions (kg CO_2)	
	Site A	Site B
Material	1.012×10^5	1.012×10^5
Equipment	2.682×10^2	2.209×10^2
Soil	3.955×10^5	1.688×10^5

As observed in Fig. 4, the highest amount of CO_2 was emitted during cofferdam construction and construction equipment constitutes the largest fraction of emissions among materials, transport, and equipment in site A. In site B, emissions from the foundation process were the highest and most emissions was caused by the materials. The equipment part in site A and the materials part in site B contribute the most to the total emissions of the entire process. This difference in the emissions characteristics between the two sites is due to the difference between the cofferdam process and the foundation process. CO_2 emissions from the construction of a relocating road in site B were estimated to be much lower than those in site A because the scale of construction in site A is relatively larger than that in site B. The embankment and spillway processes were also major sources of emissions for both sites.

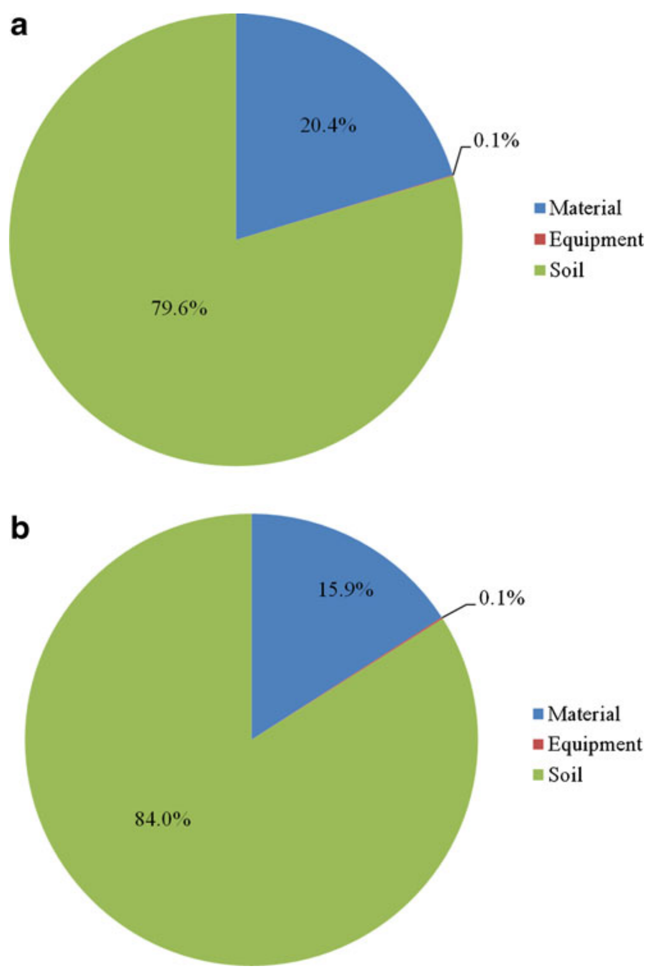

Fig. 6 Characteristics of CO_2 emissions for transport part in site A (**a**) and site B (**b**)

4.3 Characteristics CO_2 estimation for individual parts

4.3.1 Materials part

To evaluate emissions characteristics, the entire process was divided into three parts: materials, transport, and equipment. The material part was analyzed first. In the materials part, ready-mixed concrete, rebar, asphalt concrete, cement, and steel pipe were selected as major materials, and other materials were not sorted. The missions from individual materials in each site are shown in Table 5, and Fig. 5 presents the distribution of CO_2 emissions for each material.

Major construction materials (ready-mixed concrete, rebar, asphalt concrete, cement, steel pipe) accounted for 48.5 % of the total emissions for the materials part, while the other materials accounted for the remaining half of the total emissions in site A (Fig. 5a). This is because other expensive materials (rubber weir, water pump, etc.) were used in the construction of a water supply, pumping station, and appurtenance. RMC and rebar, which are mainly used in construction, contributed the first and the second highest emissions among major materials, respectively.

Major construction materials account for most of the total emissions (99.8 %). Cement constitutes the highest fraction of total emissions (85.3 %) among materials in site B because large amounts of cement were used in the foundation process and the basic unit of CO_2 emissions for cement is much greater than the basic units of other construction materials. This is also the reason why the materials part is the greatest contributor to the emissions of site B.

4.3.2 Transport part

The transport part was also analyzed. The transport part was divided into materials transport, equipment transport, and soil transport. Materials transport and equipment transport indicate the CO_2 emissions generated while moving materials or equipment from an area of procurement to a field of construction. Soil transport was defined as the movement of soils from outside to or within the field of construction. Table 6 shows the CO_2 emissions for each transport and process in each study site.

As shown in Fig. 6, the highest emissions in the transport part are due to soil transport for both sites. This is because the amount of soil transported is dominantly large although the transporting distance was so relatively short. In contrast, the distances for materials and equipment transport were long but the quantity was very small. Thus equipment and material transport contributed relatively small portion of the total CO_2 emissions as compared to that from soil transport.

4.3.3 Equipment part

The CO_2 emissions from equipment operation were estimated based on the amounts of energy sources estimating amount of energy resources (diesel, gasoline, and electricity). In this study, back hoe, bulldozer, and roller were selected as major construction equipment. Table 7 presents estimated CO_2 emissions attributed to equipment, and Fig. 7

Table 7 Estimated CO_2 emissions for the equipment part

Division	CO_2 emissions (kg CO_2)	
	Site A	Site B
Back hoe	3.711×10^5	5.653×10^5
Bulldozer	1.247×10^5	3.315×10^5
Roller	7.048×10^4	7.048×10^4
Motor grader	2.519×10^4	2.002×10^1
Sprinkler truck	8.472×10^3	4.527×10^2
Asphalt finisher	2.114×10^3	2.093×10^2
Pump car	1.072×10^4	1.642×10^3
Crane	2.084×10^5	–
Waterjet pump	2.084×10^5	–
Vibration pile hammer	7.499×10^4	–

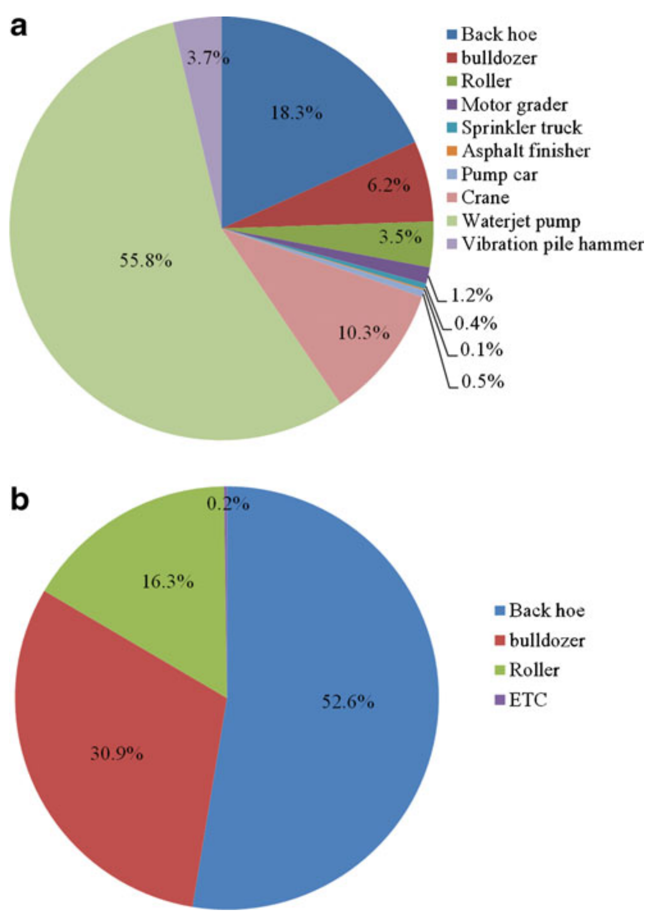

Fig. 7 Characteristics of CO_2 emissions for equipment part in site A (**a**) and site B (**b**)

shows the distribution of CO_2 emissions for each piece of equipment in each site.

The waterjet pump appeared to be the major cause of emissions (55.8 %) in the equipment part of site A, while the back hoe and crane were the second and the third largest causes, respectively (Fig. 7 (a)). A waterjet pump and crane are used cofferdam construction to pile the sheet piles. The emissions attributed to the waterjet pump were high because the corresponding operation time is long due to the low efficiency of waterjet pump during the process of piling. Thus, the emissions from equipment were more significant in site A. As shown in Fig. 7 (b), major construction equipment (back hoe, bulldozer, roller) contribute to 99.8 % of all equipment emissions and emissions attributed to other equipment were very low (0.2 %) in site B.

5 Conclusions

In this study, CO_2 emissions during construction of reservoir embankment elevation processes were estimated and characterized using EIO analysis and the dataset of the standard estimating for construction works to quantify environmental effect. The result of the estimation for a basic unit shows that cement contributes the highest emissions (1.737×10^{-2} kg CO_2/KRW) in the construction materials, while the bulldozer is the greatest (79.77 kg CO_2/h) in the construction equipment.

The total emissions from site B were slightly greater than that from site A because of the scale of construction. Most CO_2 was emitted from the water supply process among all processes in both sites. However, the cause of CO_2 emissions was different. Most CO_2 was emitted from construction materials that were used in site A, while the construction equipment was the major emission cause in site B. The emissions trends observed for major materials and equipment between site A and B were similar, except for those associated with cement and the waterjet pump. The characteristics and major causes of emissions appeared to differ among individual processes even though the similar structures are constructed. According to these results, the study findings suggest that the construction method and materials with low CO_2 emissions can be chosen based on characterized CO_2 emissions for different processes in order to reduce the amount of CO_2 emissions substantially from the construction industry. Therefore, the characterization of CO_2 emissions from agricultural infrastructure construction activities can help decision-makers identify major environmentally factors and develop environment friendly construction plans during the early stages of construction.

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